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October 14, 2016

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LLNL High Explosive Pulsed Power Capabilities and Experiments at the Ancho Canyon Test Site*

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Abstract—High explosive pulsed power (HEPP) is a unique branch of pulsed power technology that requires specialized facilities that: (1) can safely fire high explosive (HE) devices, (2) have the subsystems necessary to initiate HE, (3) have subsystems which can inject electrical energy into an experiment, (4) have a control, timing and firing system to sequence a number of events with high precision, (5) have a number of auxiliary systems needed for experiments and diagnostics (e.g. gas systems, lasers, etc.), and (6) have the infrastructure needed to capture data from a wide range of diagnostics. Since 2014, Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) have undertaken a collaborative effort to refurbish the Ancho Canyon Point 88 firing site located near Los Alamos, New Mexico. This effort led to the establishment of a state-of-the-art facility capable of fielding high energy HEPP experiments. This paper will provide an overview the Ancho Canyon facility, and highlight the HEPP subsystems, including custom initiation systems (firesets), high energy capacitor banks, and Faraday rotation diagnostics. Also, a discussion of the grounding and shielding philosophy LLNL holds for HEPP experiments, and its impact on the facility refurbishment, will be given. To date, LLNL has fielded three experiments at the refurbished Ancho Canyon Point 88 facility. Data and waveforms will be shown from a recent experiment, where a staged magnetic flux compression generator system delivered 88 mega-amperes of current to a load.

Keywords—High Explosive Pulsed Power; Magnetic Flux Compression Generator

I. Introduction

High explosive pulsed power (HEPP) is a unique subset of the pulsed power science and technology field which utilizes explosives to create fast pulses of electrical energy. Magnetic flux compression generators (MFCGs) are a specific class of HEPP which utilize high explosives (HE) to compress magnetic flux, thereby amplifying current and magnetic fields. The applications for MFCGs are numerous, and include creating multi-Megagauss magnetic fields for the purpose of studying matter in extreme states. HEPP can be used to drive equation-of-state (EOS) experiments, where shock or isentropic compression is used to study the properties of materials at high density and pressure. Lawrence Livermore National Laboratory (LLNL) has developed a suite of MFCGs to provide researchers with platforms in which to perform isentropic compression EOS experiments [1-4], namely the Full Function Test (FFT), Mini-G and Flat-Plate Generator (FPG) systems.

Facilities where HEPP experiments are conducted are unique in the fact that they must contain a broad range of capabilities and infrastructure. This includes the capabilities that one finds in a conventional pulsed power laboratory, e.g. capacitor banks, electromagnetic diagnostics, faraday cages, etc. In addition, an HEPP experimental facility must also provide the infrastructure required for high explosive tests, which aside from an area suitable for detonating HE, includes areas shielded from HE products to house experimental subsystems (e.g. a bunker), HE safety and initiation systems (firesets). Moreover, ancillary equipment for capturing other data of interest from the experimental campaign should be available, as the application requires. For LLNL's EOS work, this includes velocimetry diagnostics such as photonic Doppler velocimetry (PDV) systems.

In 2010, LLNL began fielding experiments at the Bunker 851 facility at Site 300 [5]. These experiments were focused on the FPG and Mini-G platforms discussed in [3, 4]. In 2014, LLNL focus shifted back to the FFT, a large-scale, 1000 lb HE weight experiment reported in [2]. For various reasons, the FFT experiments could not be fielded at the Bunker 851 facility. The solution, in the form of a collaborative effort between LLNL and Los Alamos National Laboratory (LANL), was to transition experimental efforts to the Ancho Canyon Point 88 test site, a facility which has a rich history of fielding HEPP experiments [6]. In late 2014, a refurbishment effort began at Ancho, with the aim of establishing a world-class facility where HEPP experiments, including large-scale high HE weight experiments, could be fielded. The result of the refurbishment, seen in Fig. 1, is a state-of-the-art facility with enhanced capabilities for HEPP experiments. As of the time of this report, LLNL has fielded three experiments at Ancho Canyon, including two FFT experiments. The Ancho Canyon facility has performed to expectations, enabling large, complex experiments to be executed with precision, and returning high quality data.
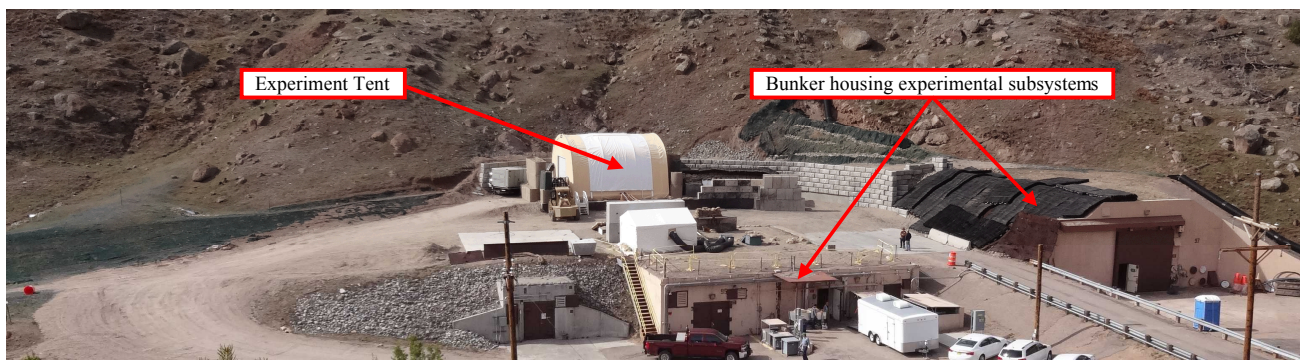
Fig. 1. The Ancho Canyon Point 88 test site being prepared for an LLNL HEPP experiment.

II. LLNL EXPERIMENTAL SUBSYSTEMS

A. Capacitor "Seed" Bank

In order to provide the initial "seed" magnetic flux into the MFCG system for compression, a modular 450 kJ capacitor bank is used. From a facility perspective, this capacitor bank supplements the capabilities of the 2.4 MJ capacitor bank already in existence at Ancho [7]. As seen in Fig. 2, the bank is comprised of four, parallel 333 μF capacitors which can be charged to 26 kV. The interconnecting buss-work is designed such that any number of the four capacitors may be used, so that the bank may be tailored to the requirements of a given experiment. The capacitors are charged via an 8 kW high voltage power supply. To protect the capacitors in case of a fault in the circuit, a fault-current limiting inductor is connected in series with each capacitor. These inductors are of the same model as those that are used as ballast inductors in the National Ignition Facility's power conditioning systems [8]. The system is housed within a Faraday cage, which is

Fig. 2. Photograph of the 450 kJ capacitor bank installed at Ancho Canyon, with 8 kW power supply external to the Faraday cage in the upper left of the picture.

maintained from the bank's location within the bunker up to the experiment area. The Faraday cage is maintained this way in order to manage the risk that electromagnetic interference (EMI) produced during discharge of the bank will upset other experimental subsystems. One important feature of the seed bank is that, during experiment execution, the ground of the bank is electrically isolated from facility ground. The margin of isolation is greater than 50 kV DC. The isolation requirement stems from the desire to eliminate ground-paths (or loops) within the facility during experiment execution. The margin of isolation is derived from actual measurements of the potential between facility ground and seed bank ground during experiments.

The energy stored in the capacitor bank is switched into the MFCG system by a solid dielectric puncture switch. The dielectric used in the switch is Mylar with a ~15 mil thickness. Actuation of the switch occurs through the use of exploding bridge-foils (EBFs). Two striplines, which each contain two 3.175 mm x 3.175 mm x 0.005 mm copper EBFs, are embedded into the switch assembly. A 6 kV, 100 J capacitor discharge unit (CDU) is used to drive the EBFs. The electrical energy deposited into the EBFs by the CDU causes them to "fuse", i.e. the copper material is driven to a plasma state through ohmic heating. The mechanical pressure of the fusing process is applied to the switch assembly, ultimately causing the dielectric failure and the switch to close. With the present design of the CDU and EBF circuit, the switch function time (from EBF fusing to switch closure) is a few microseconds, with a few hundred nanoseconds of jitter, which is suitable for the timescales of seed bank discharge (many tens to hundreds of microseconds). Since the switch and switch CDU are all electrically connected to the seed bank during an experiment, they are also electrically isolated from bunker ground with same degree of isolation as the capacitor assembly.

B. Initiation Systems (Firesets)

The MFCG platforms used by LLNL for EOS research are all staged systems, that is multiple MFCGs are connected serially to achieve the final desired output current pulse. Thus, at least two initiation systems are required for each experiment. The firesets installed at Ancho for LLNL experiments are identical to those described in [5, 9], which can be referenced for a more detailed discussion of their

design and function. For single point initiation of HE, used primarily in LLNL helical MFCGs, a 1 μF, 3.5 kV CDU is used, which is used to drive an RP-1 type detonator through ~27.5 m of Teledyne Reynolds Type C cable. For multi-point initiation of HE, which is required for LLNL coaxial MFCG designs, a 14 μF, 10 kV CDU is used. This fireset has up to fifty-four outputs. For the LLNL FFT experiments, this system is used to drive 54 RP-1 type detonators. As with the seed bank, these initiation systems are isolated from ground during an experiment, with the same margin of electrical isolation.

C. Control, Timing and Trigger Systems

Any given LLNL experiment is ultimately composed of many pulsed power (e.g. seed bank), diagnostic (e.g. PDV) and data acquisition (DAQ) systems. In order for an experiment to be successful, all of these systems must be controlled and sequenced with high reliability and temporal precision. Where possible, fiber optic or pneumatic systems are used for control, feedback and trigger distributions. These efforts are made to reduce EMI insult to subsystems during an experiment. The trigger system installed at Ancho has sub-nanosecond precision, and to-date has seen no failures after tens of thousands of triggers distributed amongst experimental subsystems.

D. Pulsed Power Diagnostics

Since HEPP experiments are inherently single-shot events, extra emphasis is placed on the implementation of diagnostics into the MFCG system and facility. In addition, the quality of the data which are captured from the diagnostics is of the upmost importance, given that the function of the experiment (intended and otherwise) is inferred almost exclusively from recorded data, post-execution. Detailed discussions of the functionality and implementation of MFCG system and facility diagnostics has been published elsewhere [5, 9], and only a few examples, relevant to the discussions in this report, will be described briefly here.

For MFCG systems, two primary diagnostics fielded are: B-dot probes and Faraday rotation sensors. The B-dot probes are used for deriving the current derivative from a measurement of the time varying magnetic field in the experiment. In general, 8-14 B-dot probes are integrated into experiments, and are typically installed in the MFCG systems. Faraday rotation sensors are used to derive the current in the system by measuring the change in the state of polarization of light due to the interaction of the light and the magnetic field generated in the experiment. There is a four sensor system installed at Ancho, which enables these measurements to be taken at multiple locations within the MFCG system.

For other experimental subsystems, a variety of diagnostics are used to measure the performance of the experiment and bunker systems. In the seed bank, for example, the individual capacitor currents are measured via current transformers, while the total current is derived from two redundant Rogowski coil measurement at the seed bank switch. A resistive voltage probe provides a measurement of seed bank voltage near the capacitors, and a capacitive voltage divider is used to measure the potential formed between the seed bank ground and bunker ground, which are electrically isolated from one another during an experiment.

To record the data from all diagnostics, 120 channels of digitizers are available at Ancho. The DAQ is composed of Teradyne digitizers [10], with either 2 GS/s (8-bit) or 400 MS/s (14-bit) sample rates. The DAQ system is housed within a Faraday cage in the bunker, which is maintained all the way to the MFCG system. A few select diagnostics (e.g. B-dots) are hard-wired to the digitizers, while a majority of diagnostic signals are transmitted into the Faraday cage optically. Once in the Faraday cage, optical signals are converted back to electrical signals and recorded on the digitizers.

E. Additional Diagnostic Systems

The primary system for diagnosing the EOS load is PDV in LLNL experiments. At Ancho, there exists the capability to field hundreds of channels of PDV on a given experiment, of both the conventional [11] and multiplexed [12] technologies. Livermore experiments executed thus far have only required tens of PDV probes.

Another diagnostic, which was just recently fielded on LLNL experiments, is an HE shock probe. This sensor is used to measure the arrival of the detonation front at a desired location in the MFCGs. The sensor is composed of a conventional multi-mode (62.5/125 μm) fiber optic cable, with one end having a standard ST/UPC connecter, and the other end having only a ferrule-optical fiber termination. The tip of the latter is coated with 150 nm of aluminum. As discussed in [13], these probes provide a fast-rise (nanosecond range) optical signal upon arrival of the HE detonation front at the probe. For experiments at Ancho, these probes are used to provide information on HE burn timing and symmetry in the MFCG systems.

III. LLNL EXPERIMENTS AT ANCHO CANYON

To-date, LLNL has conducted three experiments at the refurbished Ancho Canyon Point 88 test site, including two FFT experiments. The facility has performed to expectations, with high quality data captured during each experiment.

Figure 3 shows two sets of waveforms captured from the seed bank from an LLNL FFT experiment. The upper plot shows an overlay of the integrated Rogowski coil signals with the sum of the individual capacitor currents. The data are within 1-2% of one another during the MFCG seeding phase. The lower plot shows the measured potential difference between the seed bank ground and facility ground during the experiment. Note that the peak voltage seen is roughly -30 kV, which illustrates the need for high voltage isolation of the system.

Figures 4 and 5 shows the current and current derivative waveforms taken from the staged MFCG system during an LLNL FFT experiment. In Fig. 4, an overlay of current derivative waveforms, taken from B-dot probes and Faraday rotation sensors, is presented. One aspect of these waveforms that speaks to the fidelity of the captured data is the quality of the current derivative taken from the processed Faraday rotation data. Faraday rotation is a direct measurement of
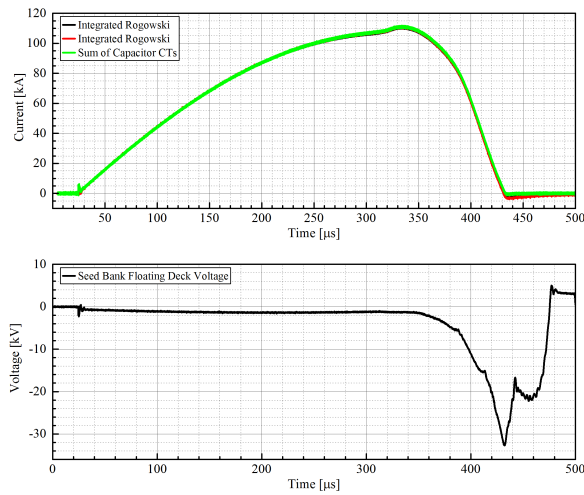
Fig. 3. Upper: current waveforms captured from seed bank discharge (traces superimposed). Lower: voltage waveform of the potential difference between seed bank ground and bunker ground.

current, thus the waveform presented in the figure was obtained by taking the derivative of the processed data. Typically, taking the derivative of measured data results in extremely "noisy" waveform, due to the amplification of noise that is present in the original data. Here, one finds that the current derivative of the Faraday rotation data has a high signal-to-noise ratio, and is in excellent agreement with B-dot probe data. The waveforms presented in Fig. 5 show an overlay of current data as taken from the B-dot and Faraday rotation sensors. The waveforms are in excellent agreement, and showed less than a 1% difference at peak current, which was ~88 MA in this particular experiment.

IV. CONCLUSION

In conclusion, LLNL and LANL have collaborated to refurbish the Ancho Canyon Point 88 test site located near Los Alamos, New Mexico. The facility is operational, and has conducted three LLNL experiments thus far, with more
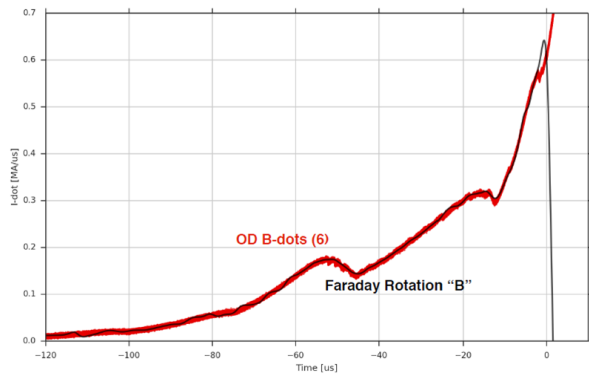

Fig. 4. Overlay of current derivative waveforms, as derived from B-dot probes and Faraday rotation sensors, for helical MFCG operation during an LLNL FFT experiment. Note the discrepancy in the data at the "0" marker on the abscissa occurs due to the crowbar of the second MFCG stage, whereupon the two diagnostics are measuring separate circuits.
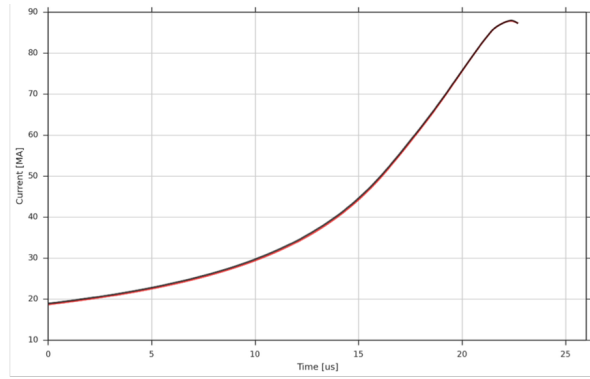

Fig. 5. Overlay of current waveforms, as derived from B-dot and Faraday rotation sensors, for the coaxial MFCG stage of an LLNL FFT experiment.

planned in the near future. Additional infrastructure has modernized the facility, enabling complex, valuable experiments to be conducted reliably and expeditiously, with high quality data return.

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